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SELF-PUMPED PHOTOREFRACTIVE REFLECTION GRATINGS IN Fe:$KNbO_3$ (PREPRINT)

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Hardened Materials Branch
Survivability and Sensor Materials Division

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MATERIALS AND MANUFACTURING DIRECTORATE
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14. ABSTRACT

- High gain confirmed in off-axis geometries for Fe:$KNbO_3$
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane*
- Large apparent variation in the effective trap density with crystal angle*
- Modified theory gives a good fit to experimental data*
- Mechanism for trap density anistropy is uncertain, but may be due to stochastic layering of impurities during crystal growth*, or from the Franz0Keldysh Effect

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$KNbO_3$, Electro-Optic Coefficient Potassium Niobate

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Self-Pumped Photorefractive Reflection Gratings in $Fe:KNbO_3$

THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

Materials & Manufacturing Directorate
Hardened Materials Branch

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•23 – 25 August 2006

•Sand Key, Florida

Outline

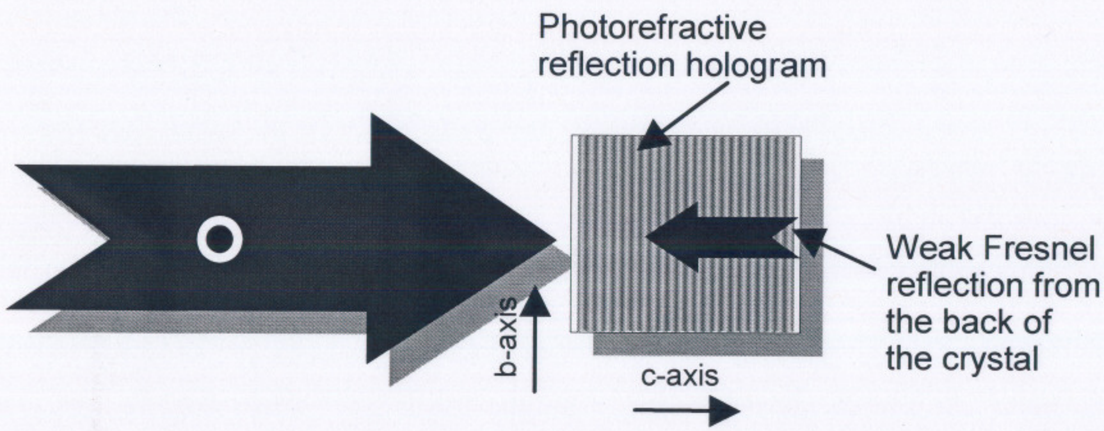
- Potassium niobate as a photorefractive
- Theory
- Off-axis geometries
- Experiments
- Results
- A controversial suggestion……
- Discussion
- Conclusion (confusion?)

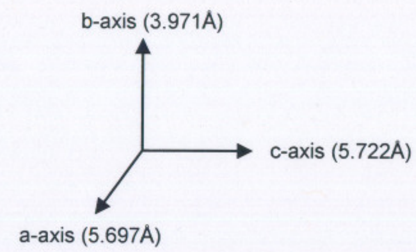
Potassium niobate as a photorefractive

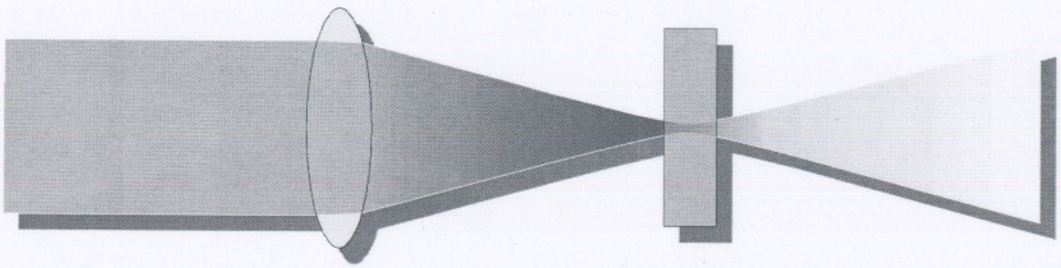
- High trap density
  - Allows efficient counter-propagating gratings to be written
    - Scope for further improvement of trap density!
- High sensitivity
  - Fast response times (~50μsec)
- Broad spectral response
  - 400nm - ~700nm (with Fe doping)
  - 400nm - >700nm? (with Ni doping)
- Difficult to grow reproducibly
  - Program under way to fix this (looks very promising!)
    - Series of 4 crystals now grown with almost identical performance

Geometry

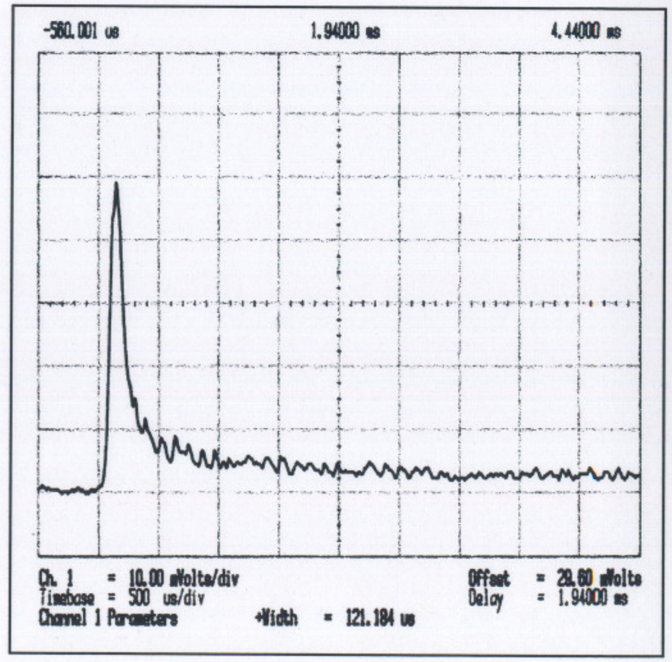
- Self-pumped two beam coupling







Focal plane geometry



Standard theory

- Optical fields

$$E_s(z,t)=\frac{1}{2}A_s(z,t)\exp i(-kz-\omega t)+c.c$$

$$E_p(z,t)=\frac{1}{2}A_p(z,t)\exp i(+kz-\omega t)+c.c$$

- Intensity fringes

$$I(z,t)=\left(I_s+I_p\right)\left(1+\frac{A_sA_p^*}{I_s+I_p}\exp\left(2ikz\right)+c.c.\right)$$

$$\frac{dN_d^+}{dt}=s\left(I+I_{Dark}\right)\left(N_d-N_d^+\right)-\gamma_r nN_d^+$$

$$\frac{dn}{dt}=\frac{dN_d^+}{dt}+\frac{1}{e}\frac{dJ}{dz}$$

$$J=e\mu nE_{sc}+\mu k_BT\frac{dn}{dz}+sI\left(N_d-N_d^+\right)e\delta$$

$$\varepsilon_s\frac{dE_{sc}}{dz}=e\left(N_d^+-N_a^--n\right)$$

(Kiev group/Kukhtarev material equations)

$A_{s,p}$ are the slowly varying amplitudes of the electric fields

Standard theory

- Solving the Kiev group/Kukhtarev's equations for the space charge field gives:

$$\frac{a}{\tau_{di}}\frac{\partial E_{sc}}{\partial t}+bE_{sc}+cm=0$$

- Where:

$$m=\frac{\sqrt{I_sI_p}}{I_s+I_p+I_{Erasure}}\exp(-i\varphi),$$

$$a=1+\frac{E_d}{E_m}-i\frac{E_0}{E_m},$$

$$b=1+\frac{E_d}{E_q}-i\left(\frac{E_0+(N_a/N_d)E_{pv}}{E_q}\right),$$

$$c=E_0+E_{pv}+iE_d$$

$$\tau_{di}=\varepsilon_s\gamma_rN_a/e\mu s(I_p+I_s+I_{Erasure})(N_d-N_a)$$

$$E_d=\frac{2\pi k_BT}{e\Lambda}$$

$$E_q=(1-N_a/N_d)\,eN_a/2k\varepsilon_s$$

$$E_{pv}=\gamma_rN_a^-\delta/\mu$$

$$E_m=\gamma_rN_a/(\mu K)$$

Standard theory

- The space charge field modifies the refractive index through the linear Pockels effect

- Substituting the modulated index into the optical wave equation gives the coupled equations for the intensities and phase:

$$\frac{\partial I_p}{\partial z} = -\alpha I_p - \frac{2\pi n^3 r_{eff}}{\lambda}\sqrt{I_p I_s}\,\mathrm{Im}\left(E_{sc}\exp(i\varphi)\right)$$

$$\frac{\partial I_s}{\partial z} = +\alpha I_s - \frac{2\pi n^3 r_{eff}}{\lambda}\sqrt{I_p I_s}\,\mathrm{Im}\left(E_{sc}\exp(i\varphi)\right)$$

$$\frac{\partial \varphi}{\partial z} = \frac{\pi n^3 r_{eff}(I_p - I_s)}{\lambda\sqrt{I_p I_s}}\mathrm{Re}\left(E_{sc}\exp(i\varphi)\right)$$

Standard theory

- In steady state the space charge field and coupled equations reduce to:

$$E_{sc}(z) = \frac{-\left(E_0 + iE_d + E_{pv}\right)m(z)}{1 + \frac{E_d}{E_q} - i\left(\frac{E_0}{E_q} + \frac{N_a E_{pv}}{N_d E_q}\right)}$$

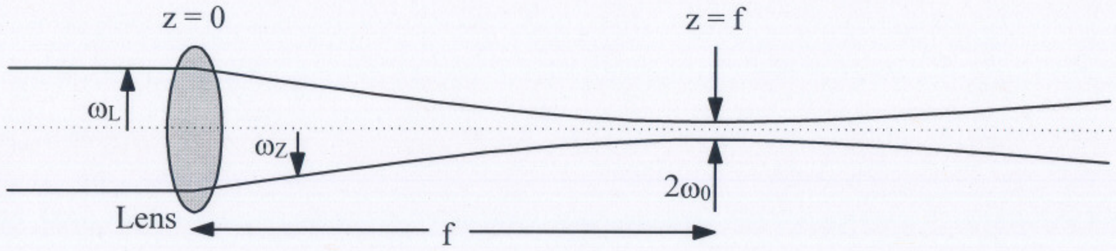
$$\frac{dI_p}{dz} = -\alpha I_p - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

$$\frac{dI_s}{dz} = +\alpha I_s - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}}$$

Where $\Gamma = \frac{2\pi}{\lambda} n^3 r_{eff} \operatorname{Im}\left(E_s\right)$

Focusing

- Focusing



$$\frac{dI_p}{dx} = -\alpha I_p - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f)I_p}{z_R^2 + (z-f)^2}$$

$$\frac{dI_s}{dx} = +\alpha I_s - \Gamma \frac{I_p I_s}{I_p + I_s + I_{Erasure}} - \frac{2(z-f)I_s}{z_R^2 + (z-f)^2}$$

Extended theory

- Piezoelectric/photoelastic contributions[1,2]

$$r_{ij}^{eff} = r_{ijk}^{S}\hat{n}_k + p_{ijkl}^{'E}\hat{n}_l A_{km}^{-1} B_m$$

$$A_{ik} = C_{ijkl}^{E}\hat{n}_j \hat{n}_l$$

$$B_i = e_{kij}\hat{n}_k \hat{n}_j$$

r_{ijk}^{S} is the clamped EO tensor

$p_{ijkl}^{'E}$ is the effective elasto-optic tensor

C_{ijkl}^{E} is the elastic stiffness tensor

e_{kij} is the piezoelectric tensor

- Scalar effective EO coefficient:

$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

1) M. Zgonik, K. Nakagawa, P. Günter, "Electro-optic and dielectric properties of photorefractive BaTiO3 and KNbO3", J. Optical Society of America B, vol. 12, no. 8, pp 1416-1421, 1995.
2) M. Zgonik, R. Schlesser, I. Biaggio, E. Voit, J. Tscherry, P. Günter, "Materials constants of KNbO3 relevant for electro- and acousto-optics", J. Applied Physics, vol. 74, no. 2, pp 1287-1297, 1993.

Extended theory

- Dielectric "constant":
  - Not a constant!
    - Varies with angle

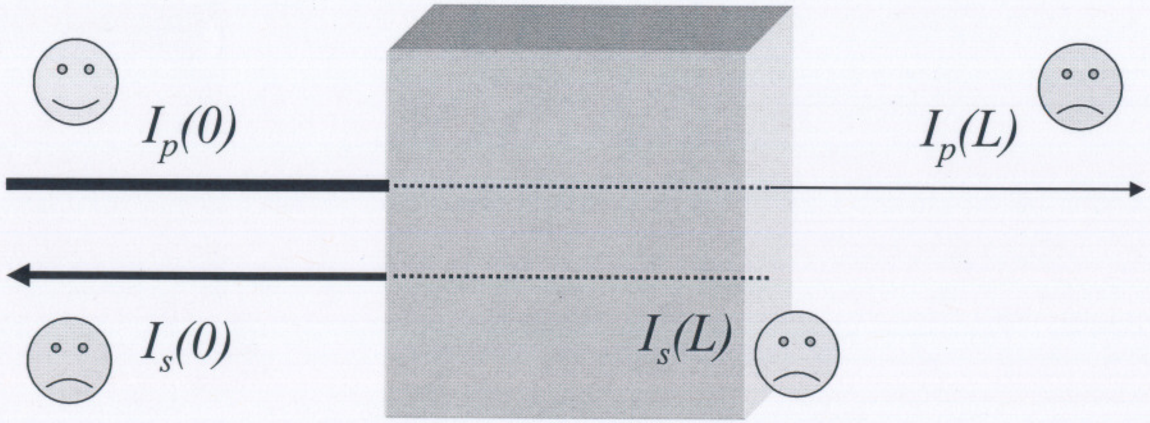
$$\varepsilon_r^{eff} = \varepsilon_{ij}^{S}\hat{n}_i\hat{n}_j + \frac{e_{ijk}e_{mnl}\hat{n}_i\hat{n}_j\hat{n}_m\hat{n}_n A_{kl}^{-1}}{\varepsilon_0}$$

ε_{ij}^{S} is the clamped dielectric tensor

- Determines the saturation field
  - Affects the space-charge field and grating phase shift

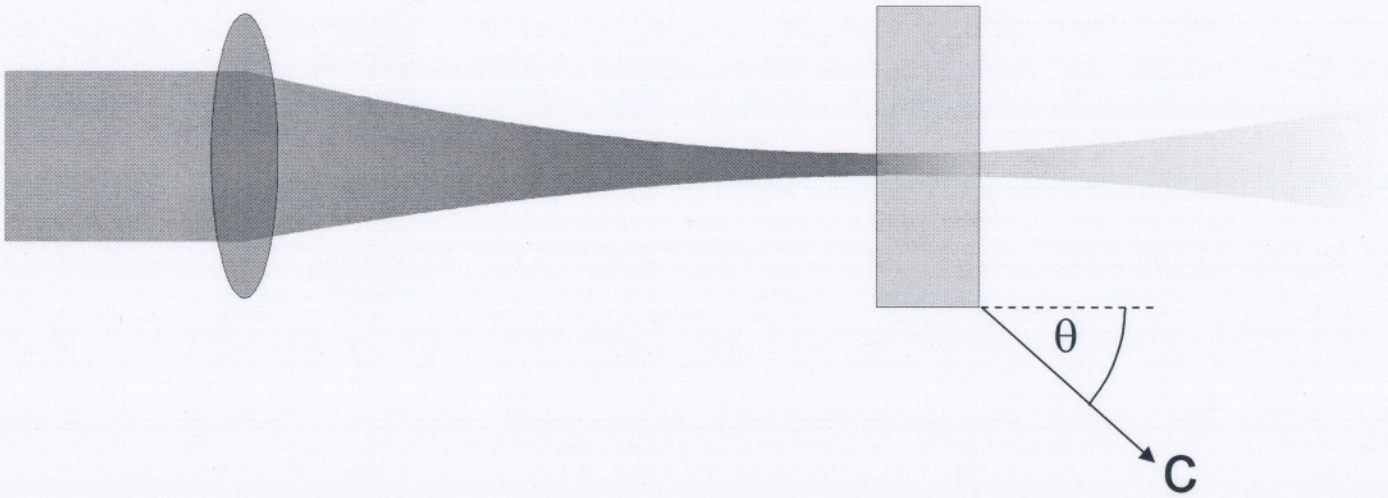
Theory solutions

- No closed form solution to the coupled equations
- Numerical solutions only
- For self pumped two beam coupling the boundary conditions are known only for the pump input
- Iterative shoot and match methods are required



Off-axis concept

- Optical gain is potentially much higher away from the c-axis

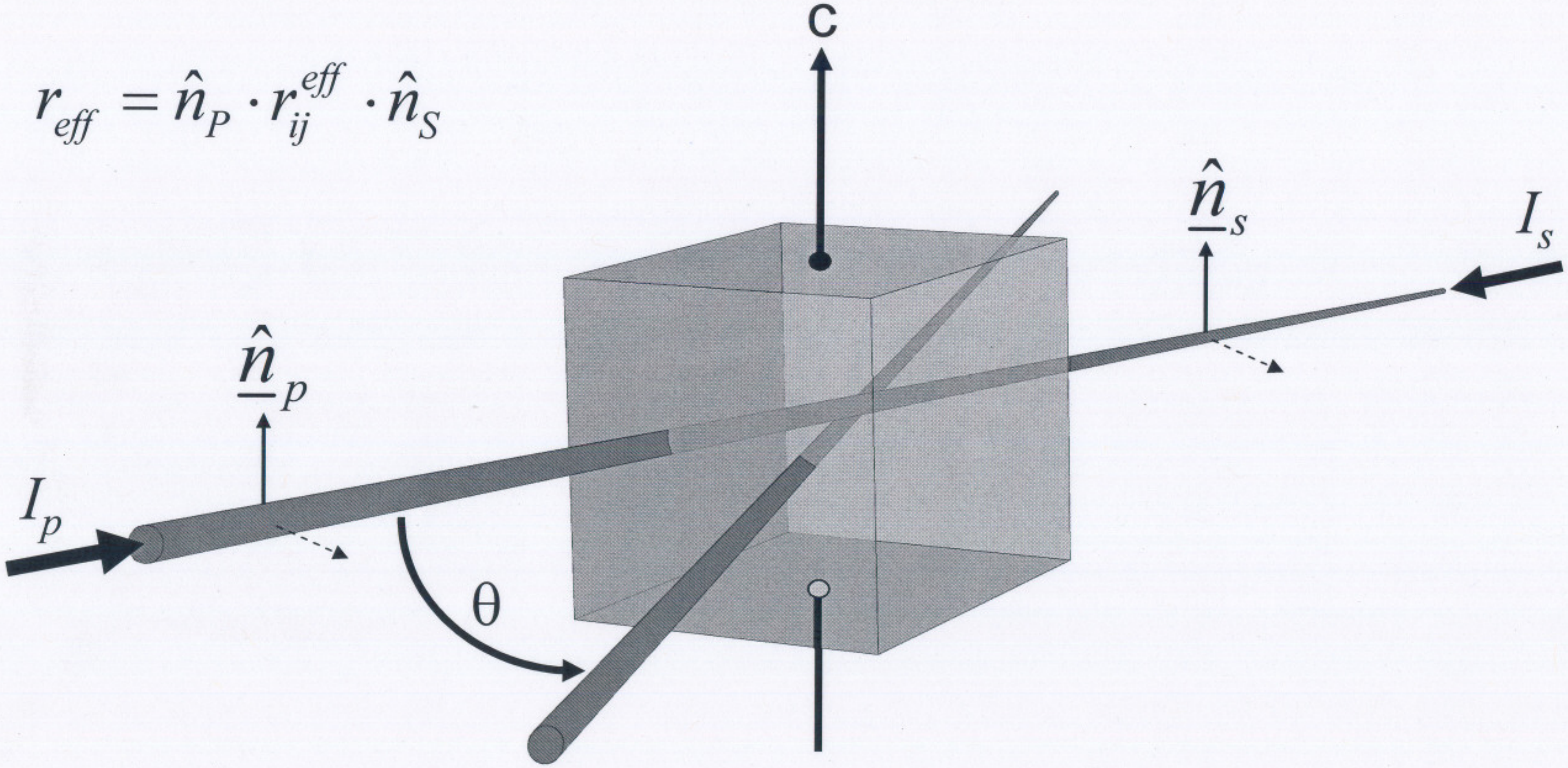


- c-axis is best for $Fe:LiNbO_3$ owing to the huge PV effect
- The same is NOT true for $Fe:KNbO_3$

Off-axis effective electro-optic coefficient

- Beam axis rotation about the c-axis:

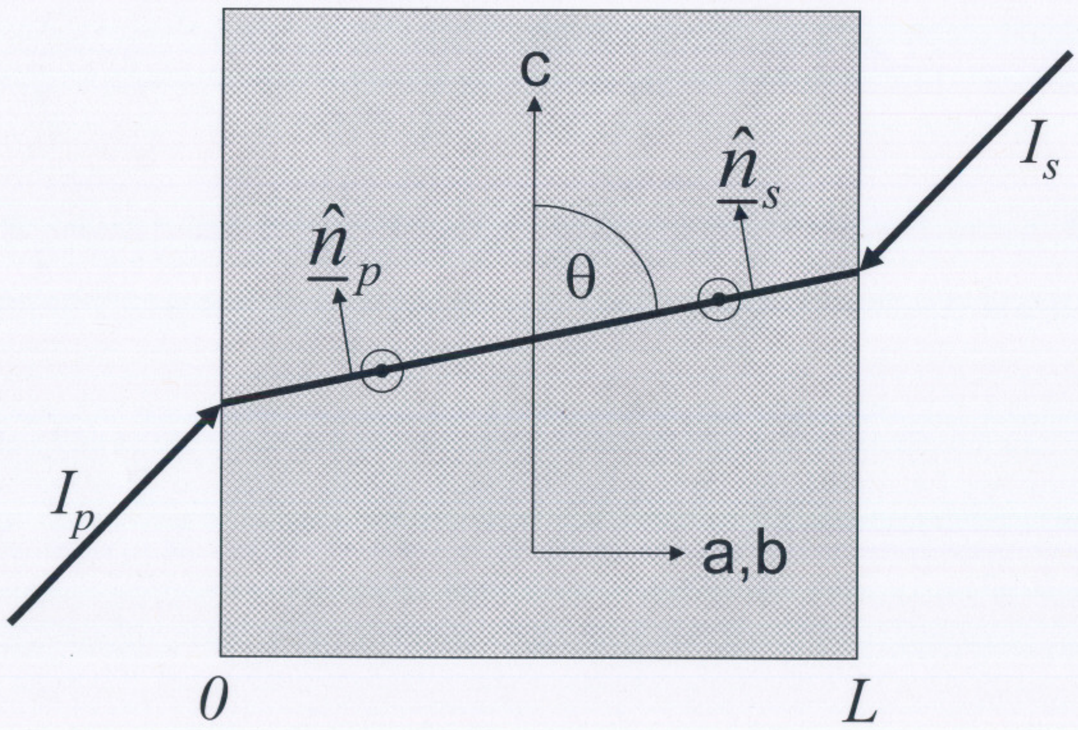
$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$



r_{eff} is <u>zero</u> for all parallel linear polarizations

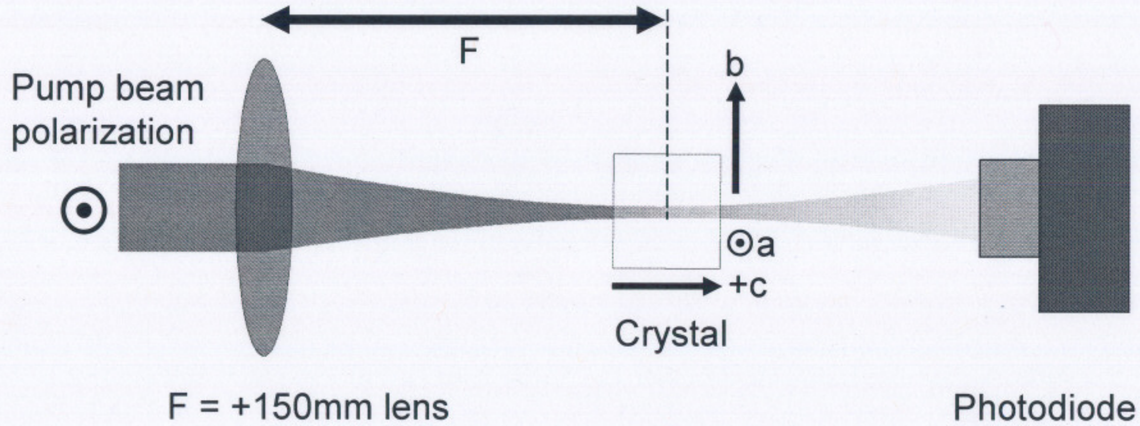
Off-axis effective electro-optic coefficient

- Beam axis rotation in the a-c or b-c planes:



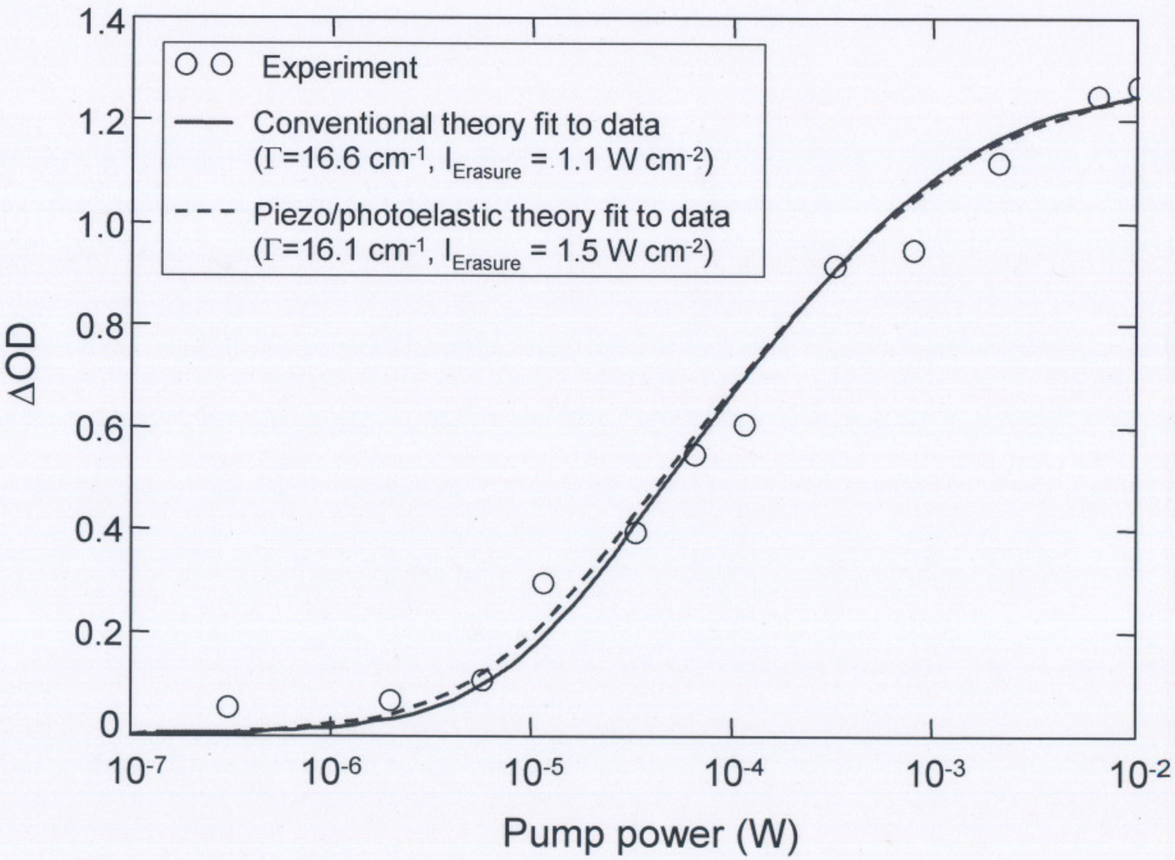
$$r_{eff} = \hat{n}_P \cdot r_{ij}^{eff} \cdot \hat{n}_S$$

Determination of Γ and $I_{Erasure}$



Determination of Γ and $I_{Erasure}$

$$\Delta OD = \log_{10}\left(\frac{T_{Linear}}{T_{SteadyState}}\right)$$

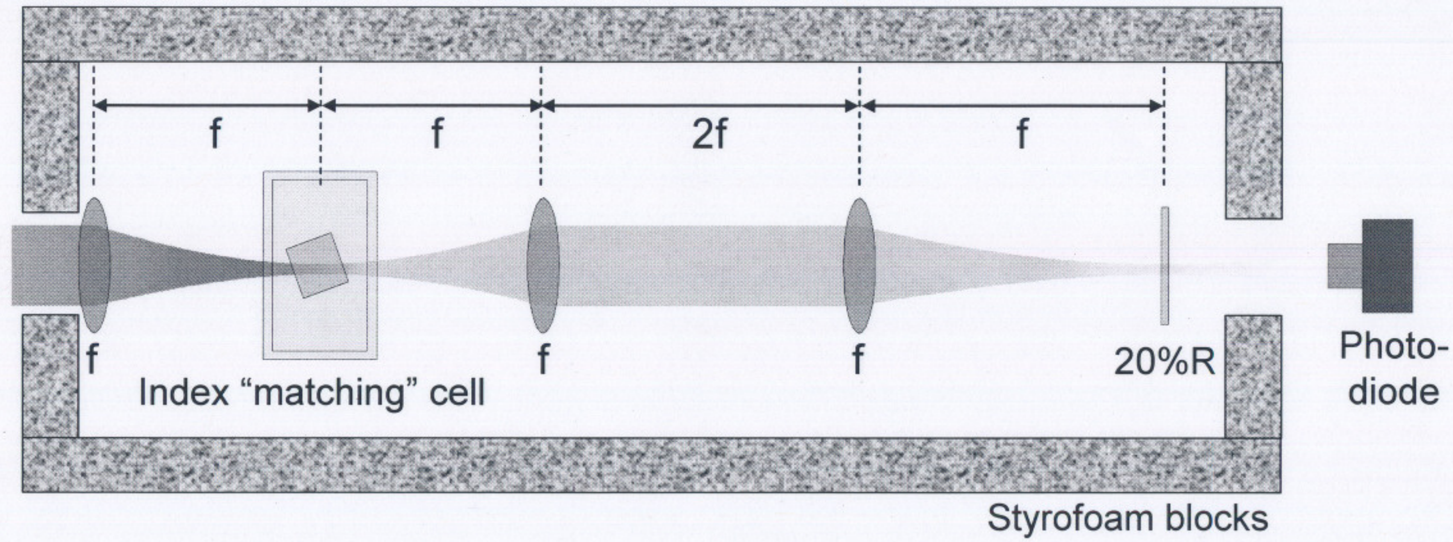


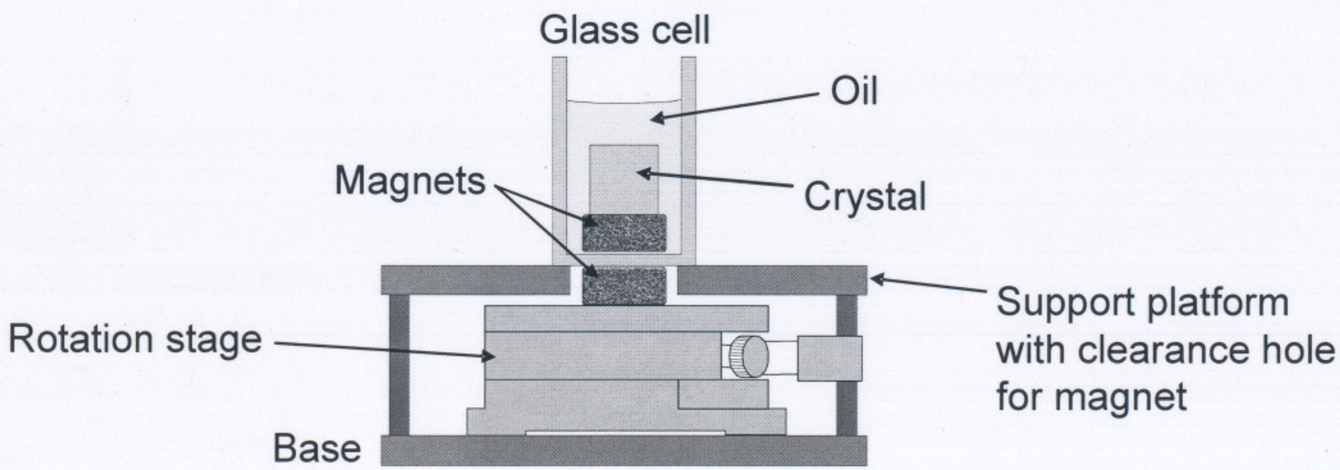
N_A (conventional) = 2.1×10^{16} cm^{-3}

N_A (piezo) = 5.0×10^{16} cm^{-3}

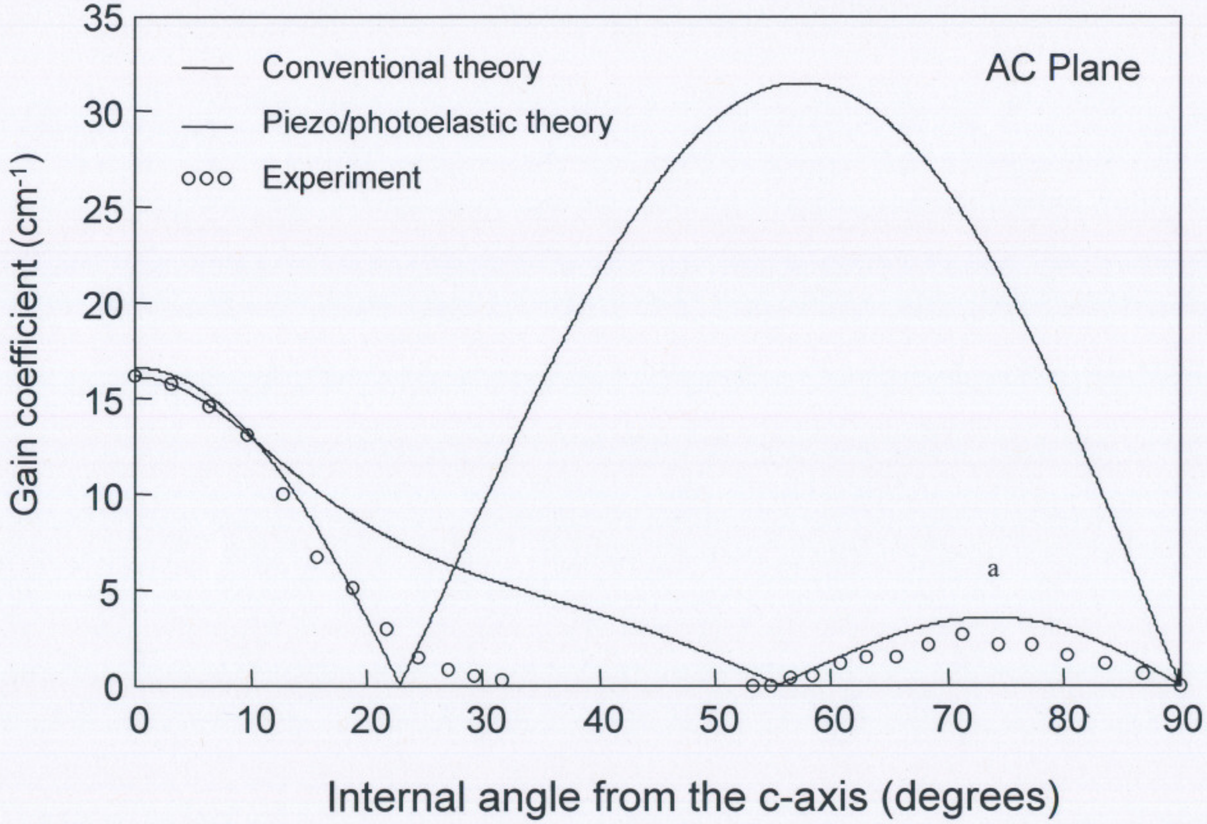
Measuring the off-axis gain in contra-directional $Fe:KNbO_3$

- Experiment:





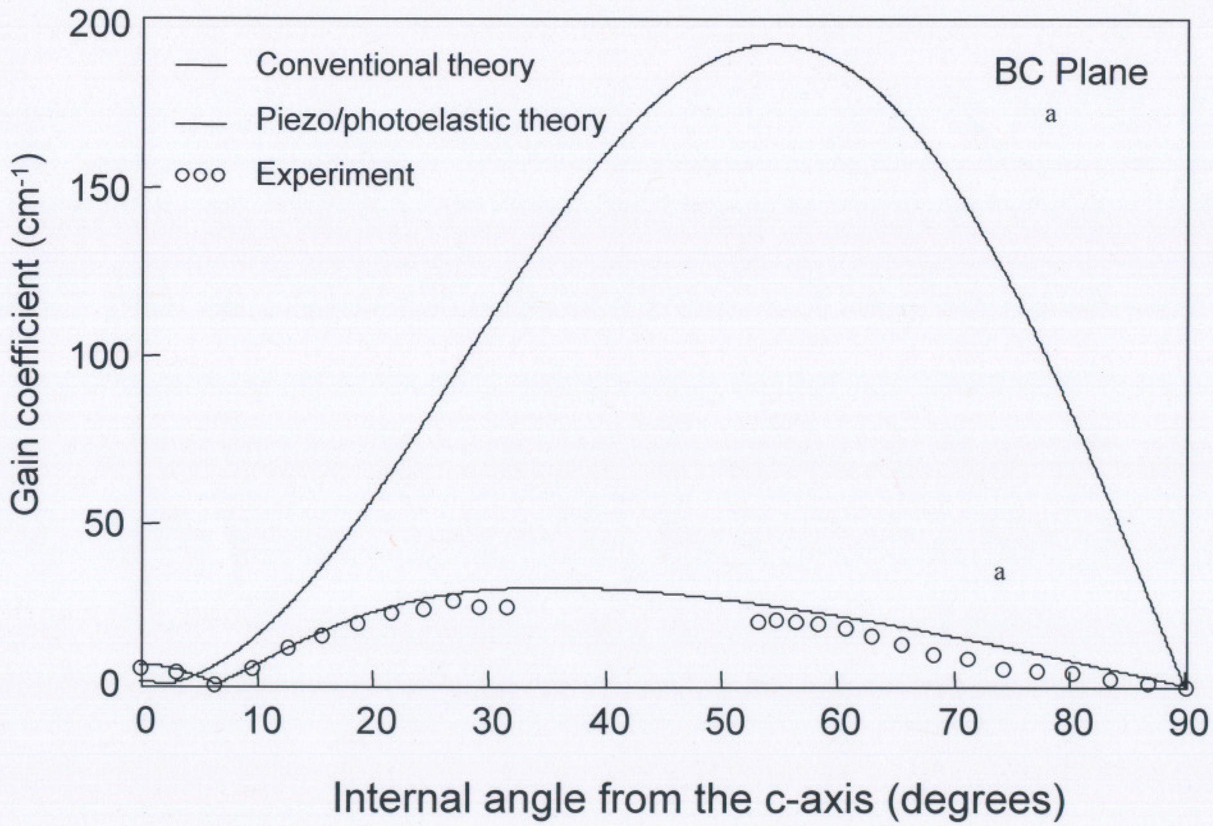
Off-axis gain results



N_A (conventional) = 2.1×10^{16} cm^{-1}

N_A (piezo) = 5.0×10^{16} cm^{-1}

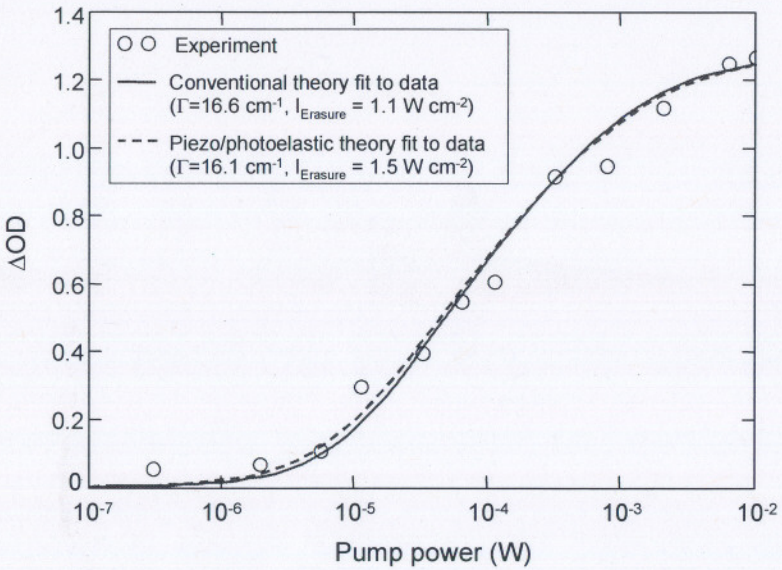
Off-axis gain results

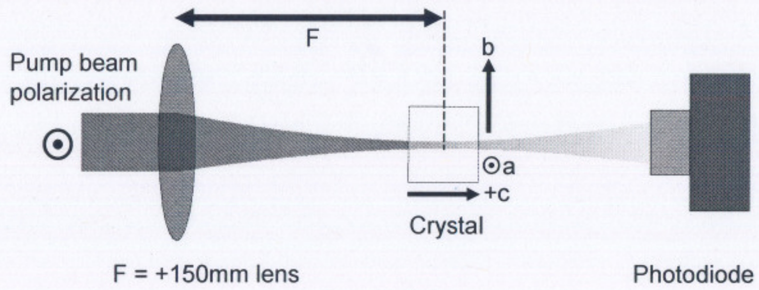


N_A (conventional) = 2.1×10^{16} cm^{-1}

N_A (piezo) = 5.0×10^{16} cm^{-1}

A controversial suggestion....

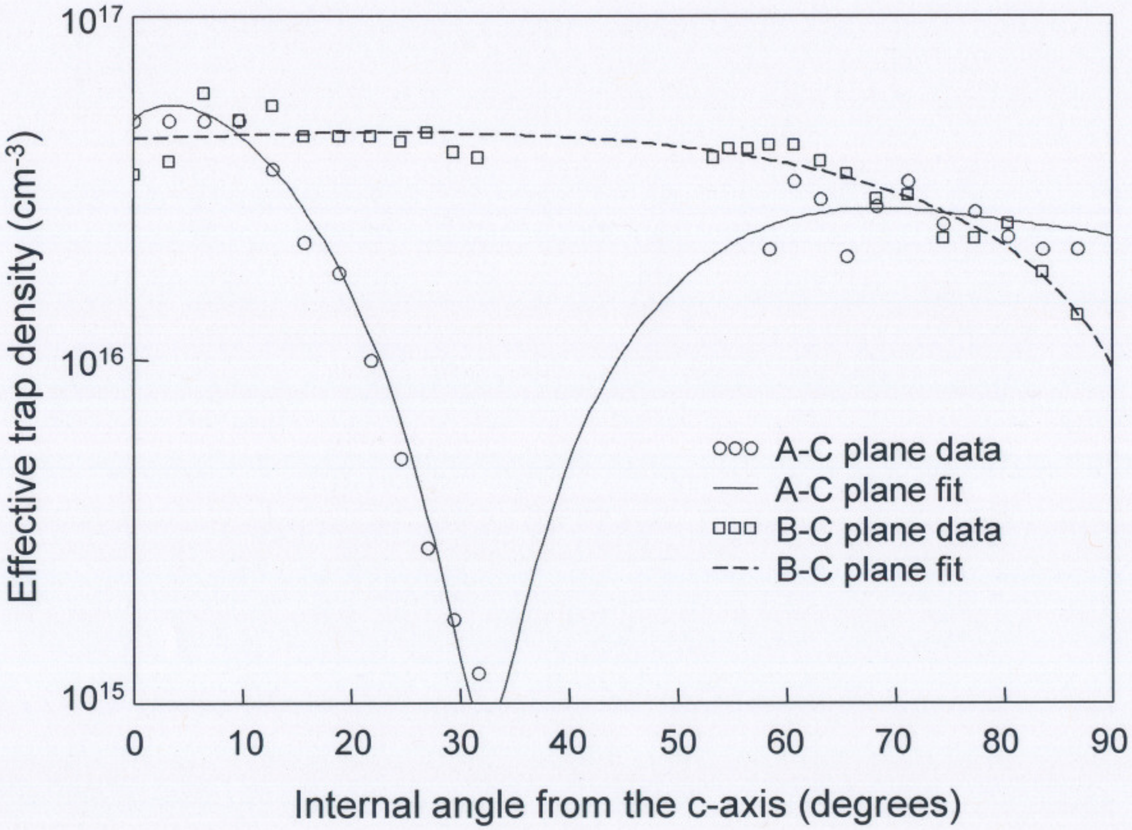




- Repeat previous measurements of Γ and $I_{Erasure}$ for all crystal angles
- Calculate the effective trap density for each crystal angle

"Conventional" transmission/reflection grating method cannot be used reliably for trap density measurements owing to admittance angular restrictions at large crystal angles and competition from rear Fresnel reflection.

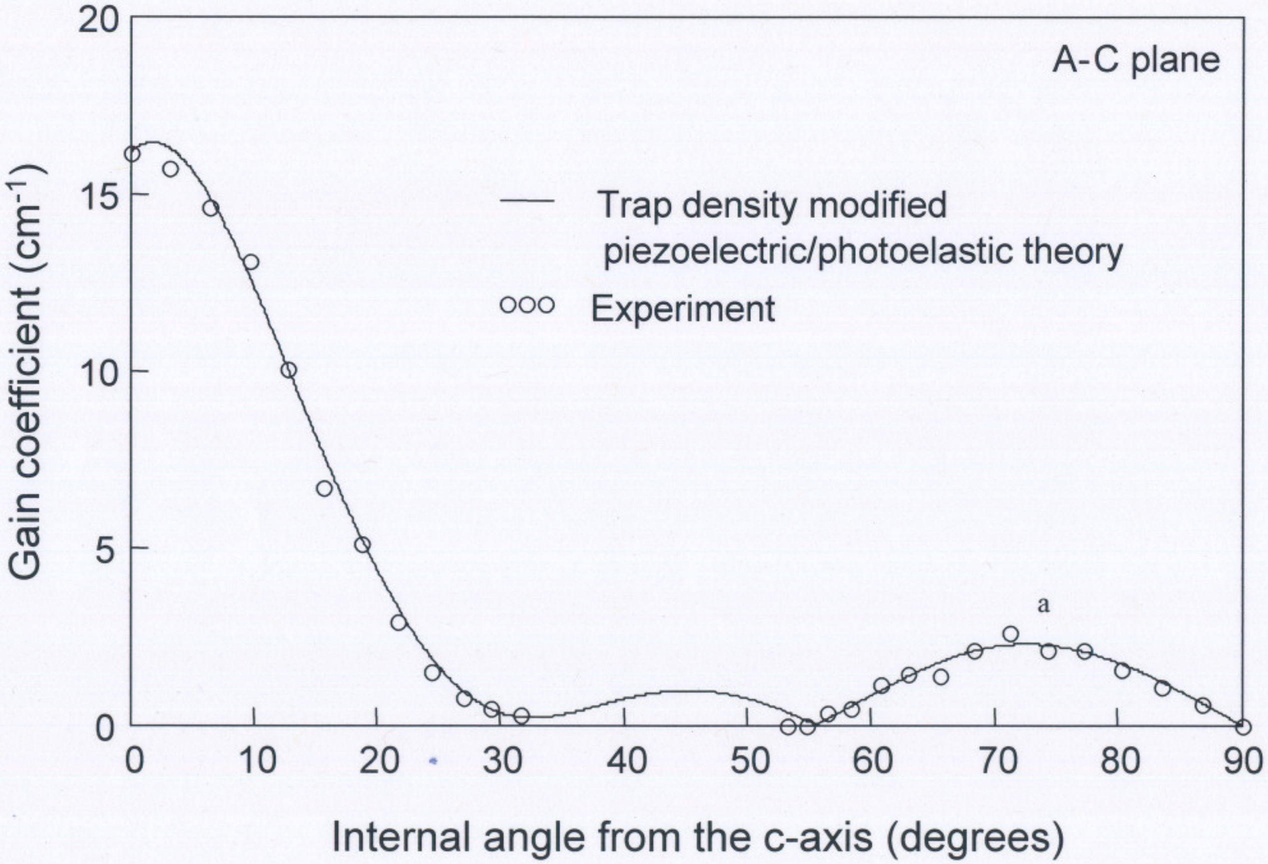
Effective trap density variations?



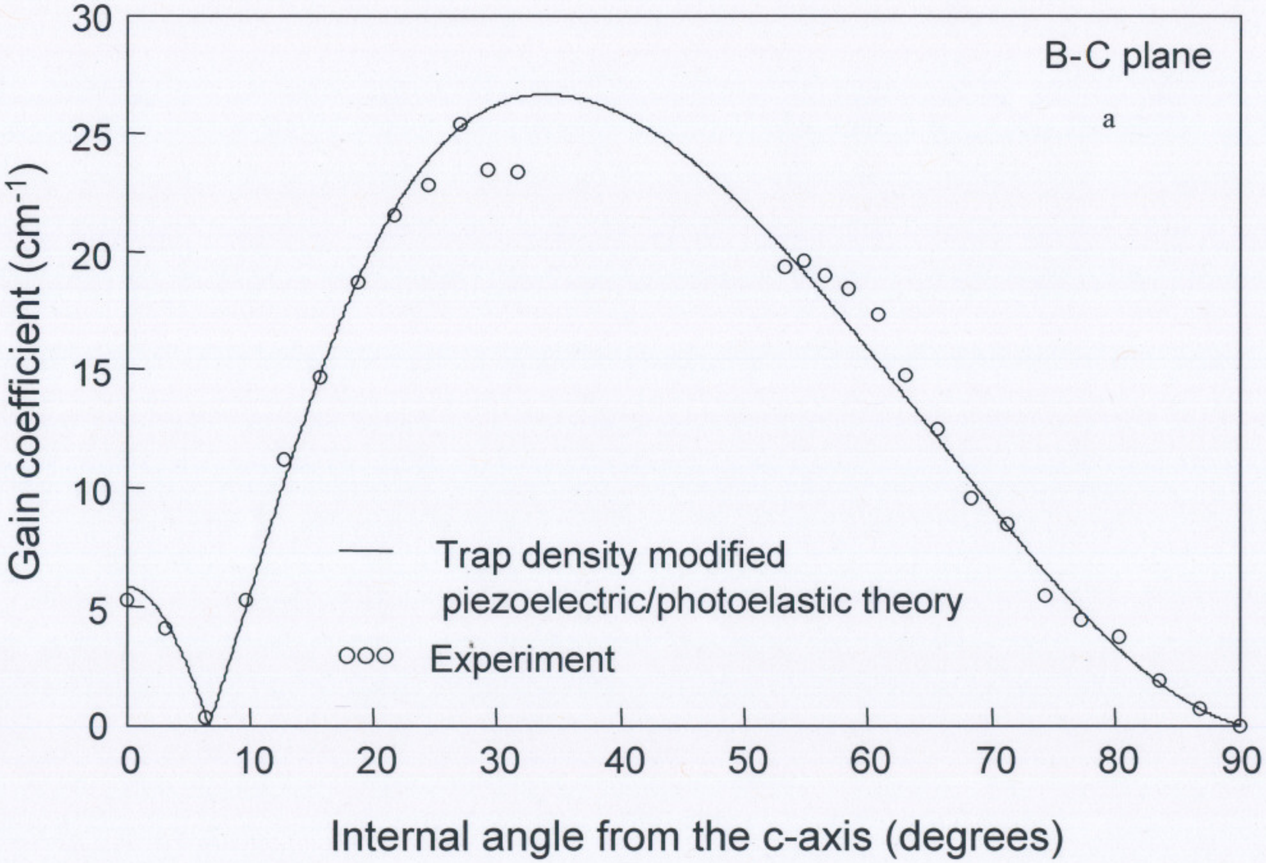
$$N_{A(AC)} = -9.09\times10^{12}\theta^6 + 3.03\times10^{15}\theta^5 - 3.85\times10^{17}\theta^4 + 2.26\times10^{19}\theta^3 - 5.67\times10^{20}\theta^2 + 3.21\times10^{21}\theta + 5\times10^{22}$$

$$N_{A(BC)} = -6\times10^{16}\theta^3 + 1\times10^{20}\theta + 4.42\times10^{22}$$

Theory modified for apparent trap density variations

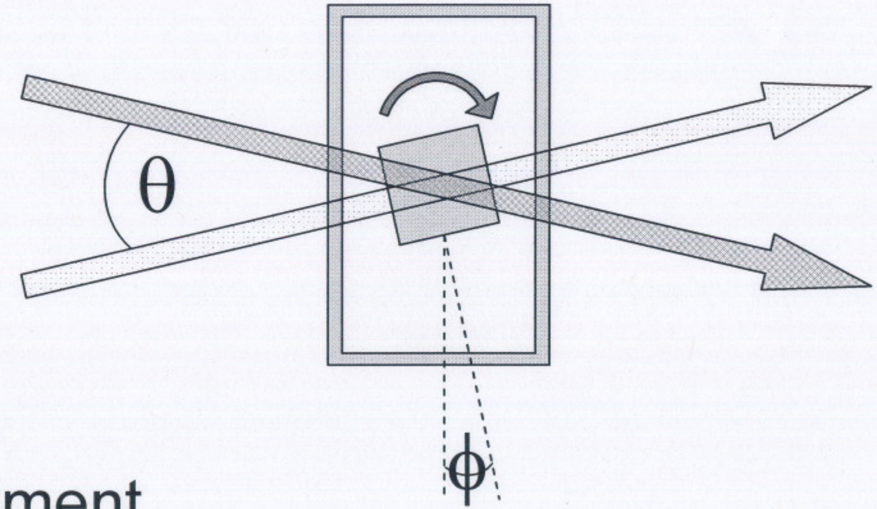


Theory modified for apparent trap density variations



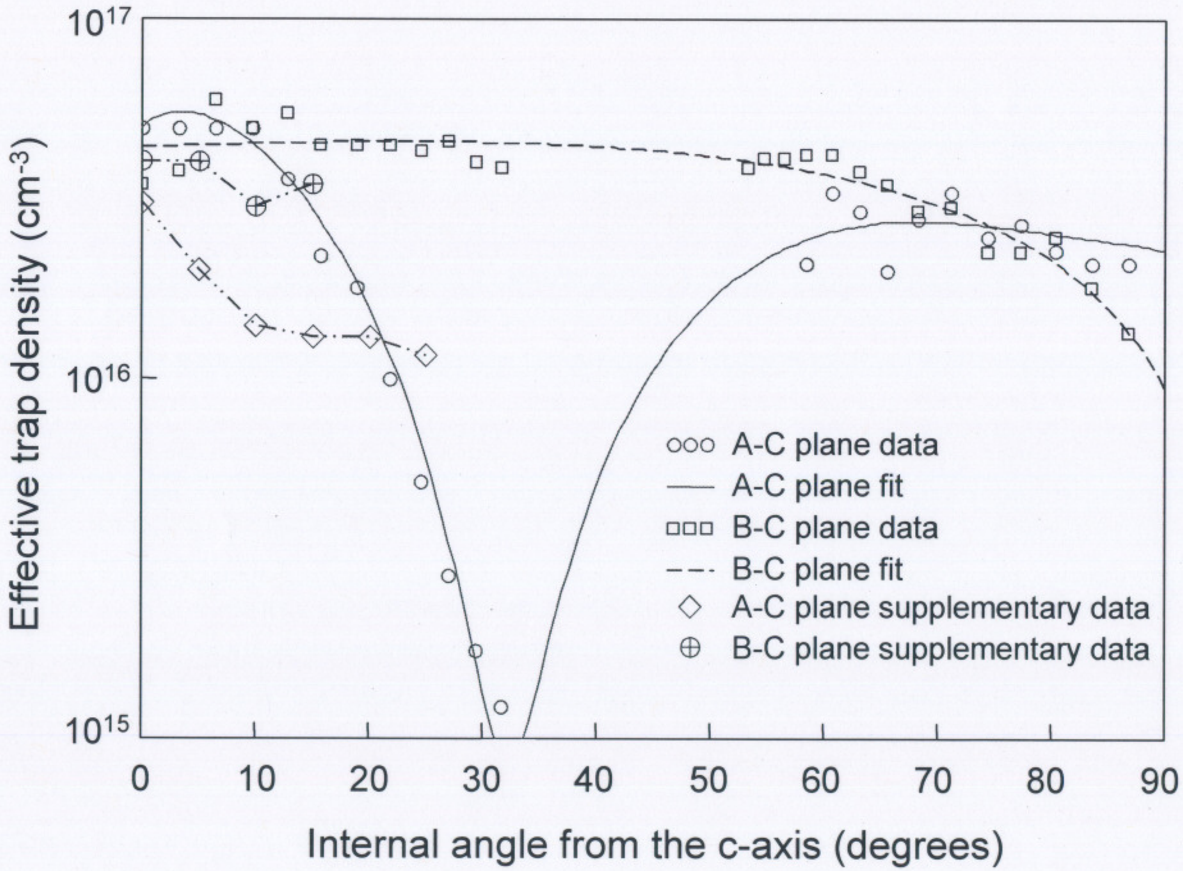
2^{nd} attempt to verify trap density variations

- Measure small signal gain as a function of grating spacing:



- Difficult experiment
  - Gain becomes very large – leads to competition from spurious beams
  - Difficult to maintain beam overlap at larger crystal angles
  - Pump and signal beam incidence angles become asymmetric, leading to a rotation of the grating k-vector. This requires a mechanical correction of the crystal angle at every measurement.

2^{nd} attempt to verify trap density variations

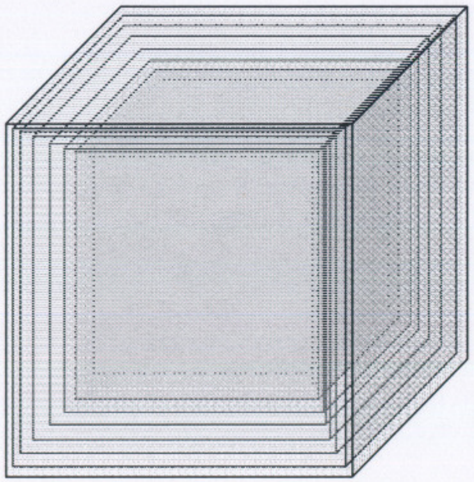


Discussion

- An *effective* trap density is possible if the charges "remember" the original polarization state
- Delocalization of charges should randomize the charge state (can they "remember" the exciting polarization?)
- Rule out electron-hole competition (gain does not reverse with grating spacing)
- Trap density anisotropy has no physical meaning unless the grating spacing is greater than the mean trap separation………. But how can this occur?

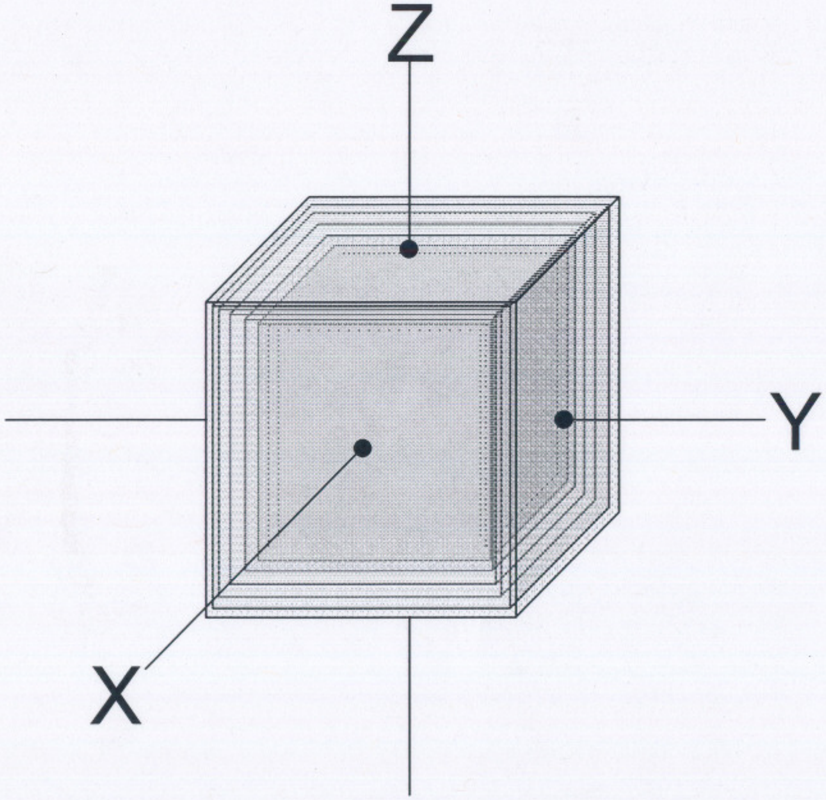
Growth induced defect layers

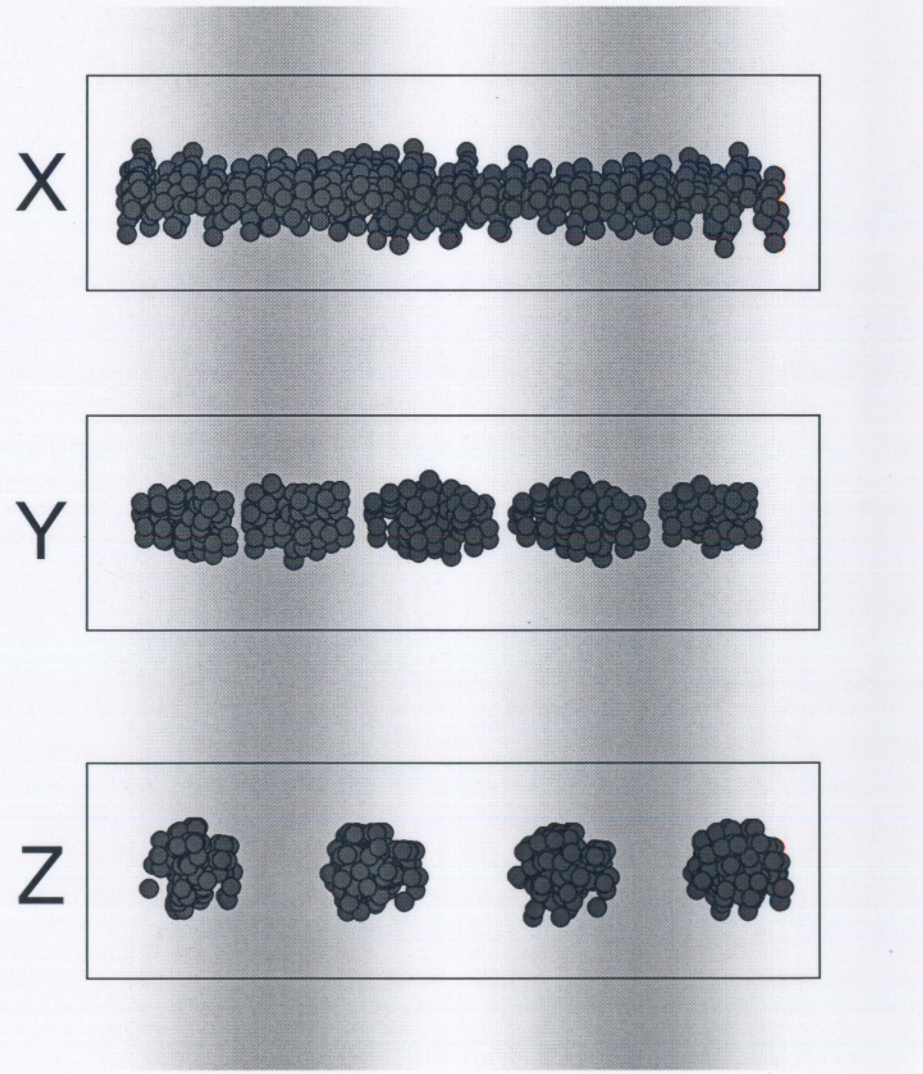
- Growth of potassium niobate does not occur smoothly
- Growth is stochastic, adding a plethora of microscopically thin layers
- Impurities (Fe) tend to segregate at the boundaries between these structures*
- It is therefore reasonable to assume the added impurities (Fe) form stratified concentrations of traps



* M. B. Mishra and S. G. Ingle, J. Appl. Phys. **45**, 5152 (1974).

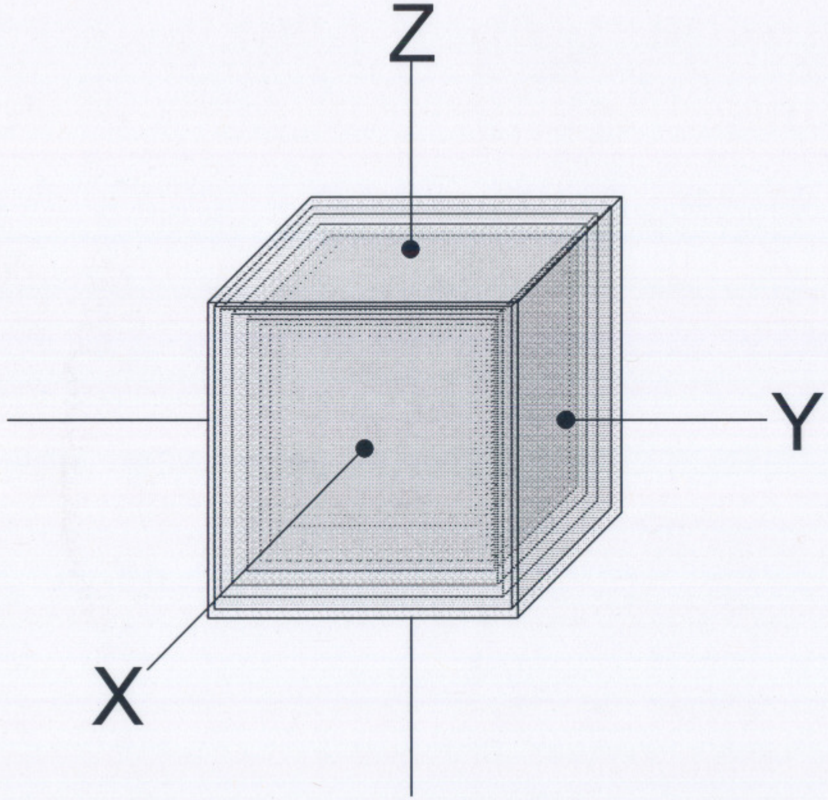
Growth induced defect layers Transmission gratings

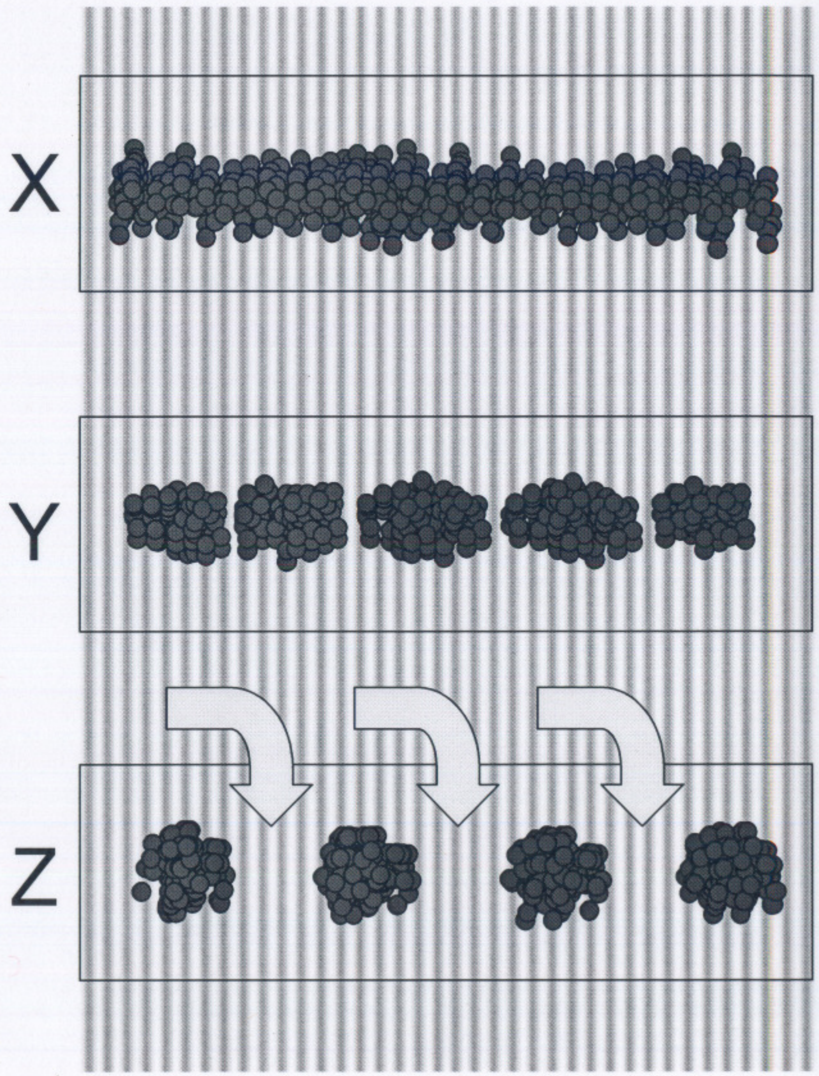




- Traps always coincide with fringes
- Average trap density remains approximately constant with direction
- Effect of defect "layers" not apparent

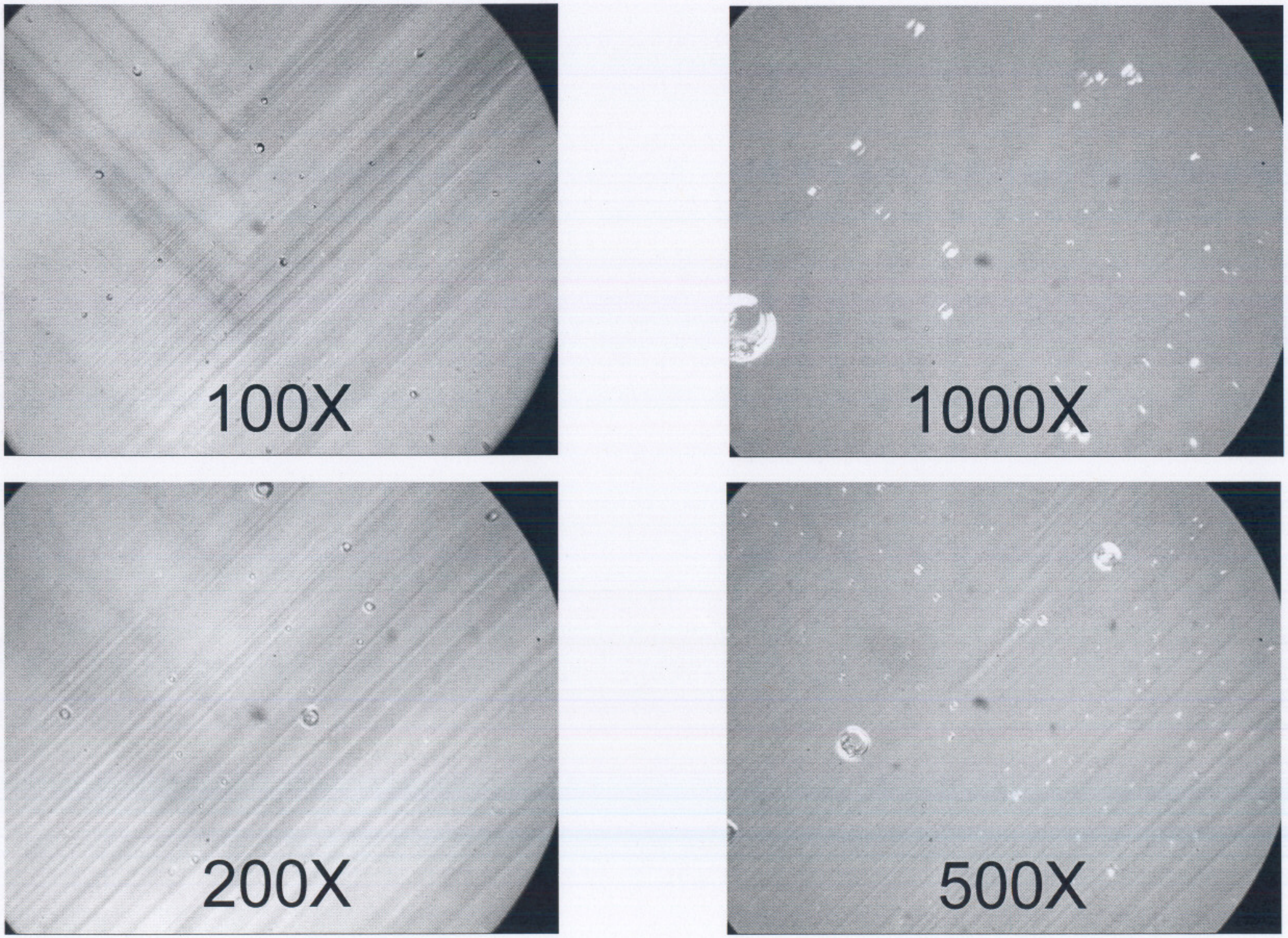
Growth induced defect layers
Reflection gratings





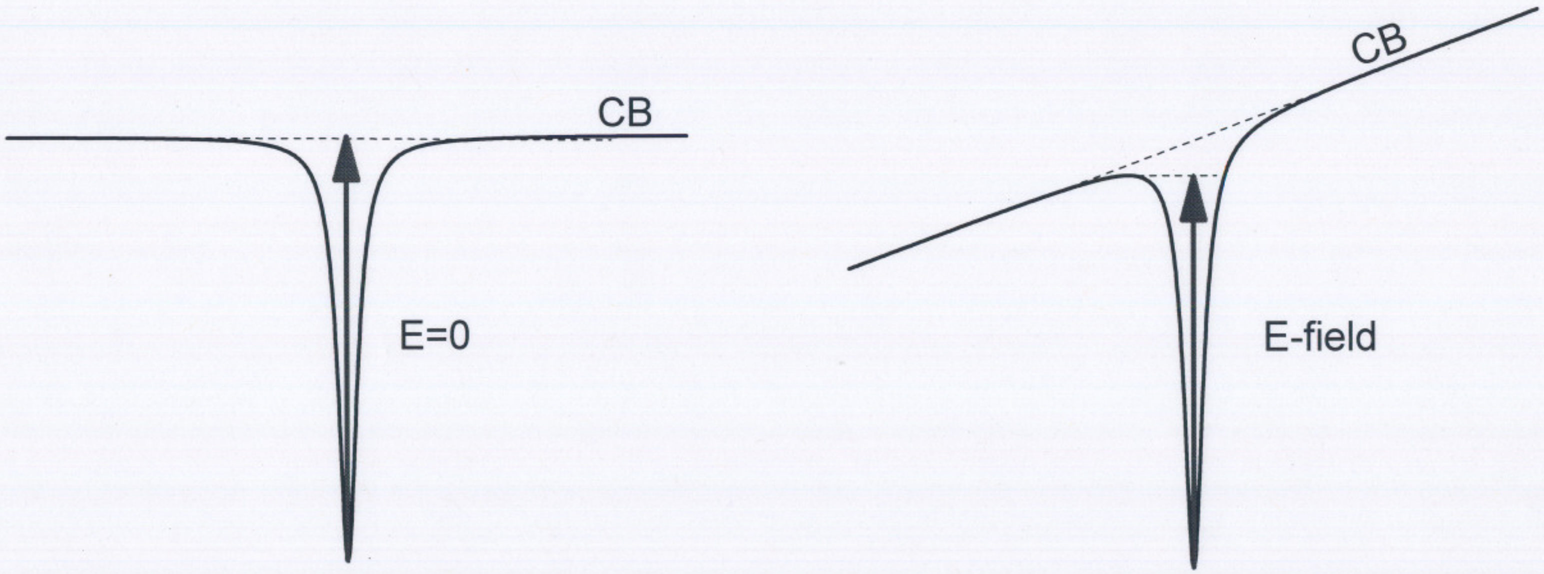
- Some fringes have a low trap density
- Local trap density becomes sensitive to direction
- Effect of defect "layers" becomes apparent

Defects in $KNbO_3$



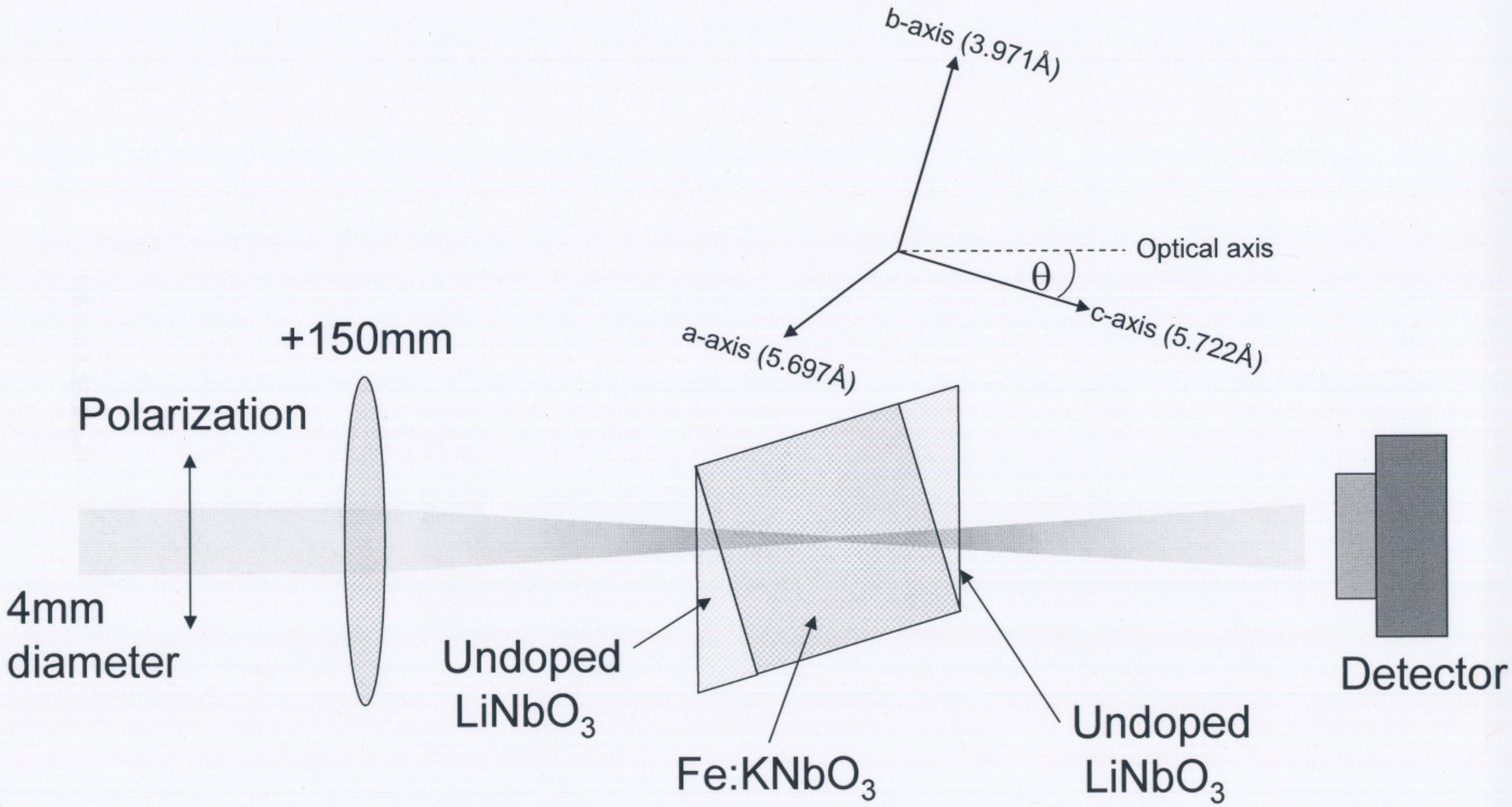
Franz-Keldysh Effect.....?

- Electric field induced absorption in bulk semiconductors
- Can ***strain*** have a similar effect? – growth and/or poling
- Strain induced trap depth – directional variation of the ***effective*** trap density

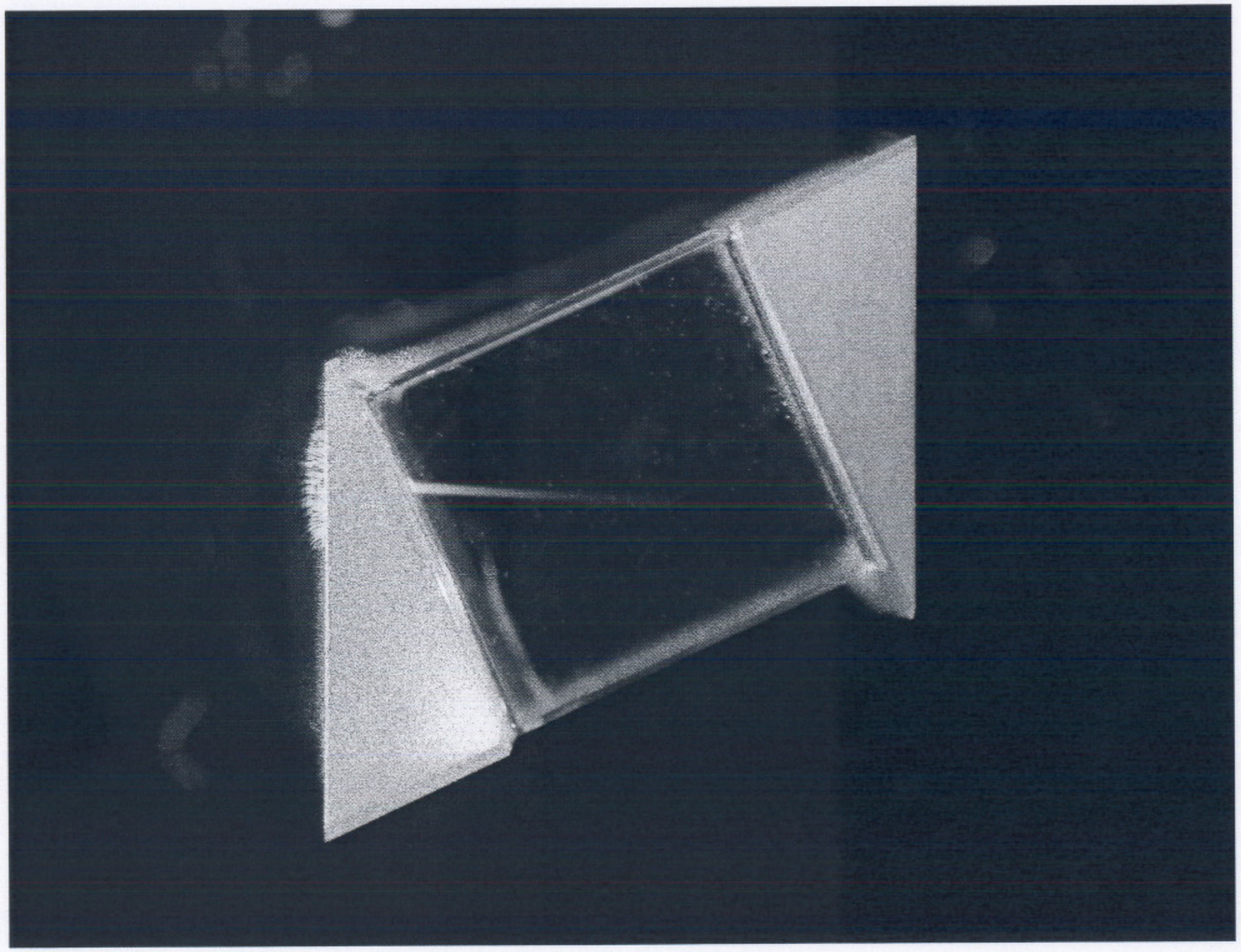


- Franz-Keldysh effect may also give a field dependent effective trap density
- Effective trap density, and hence saturation field, becomes nonlinear with grating spacing….

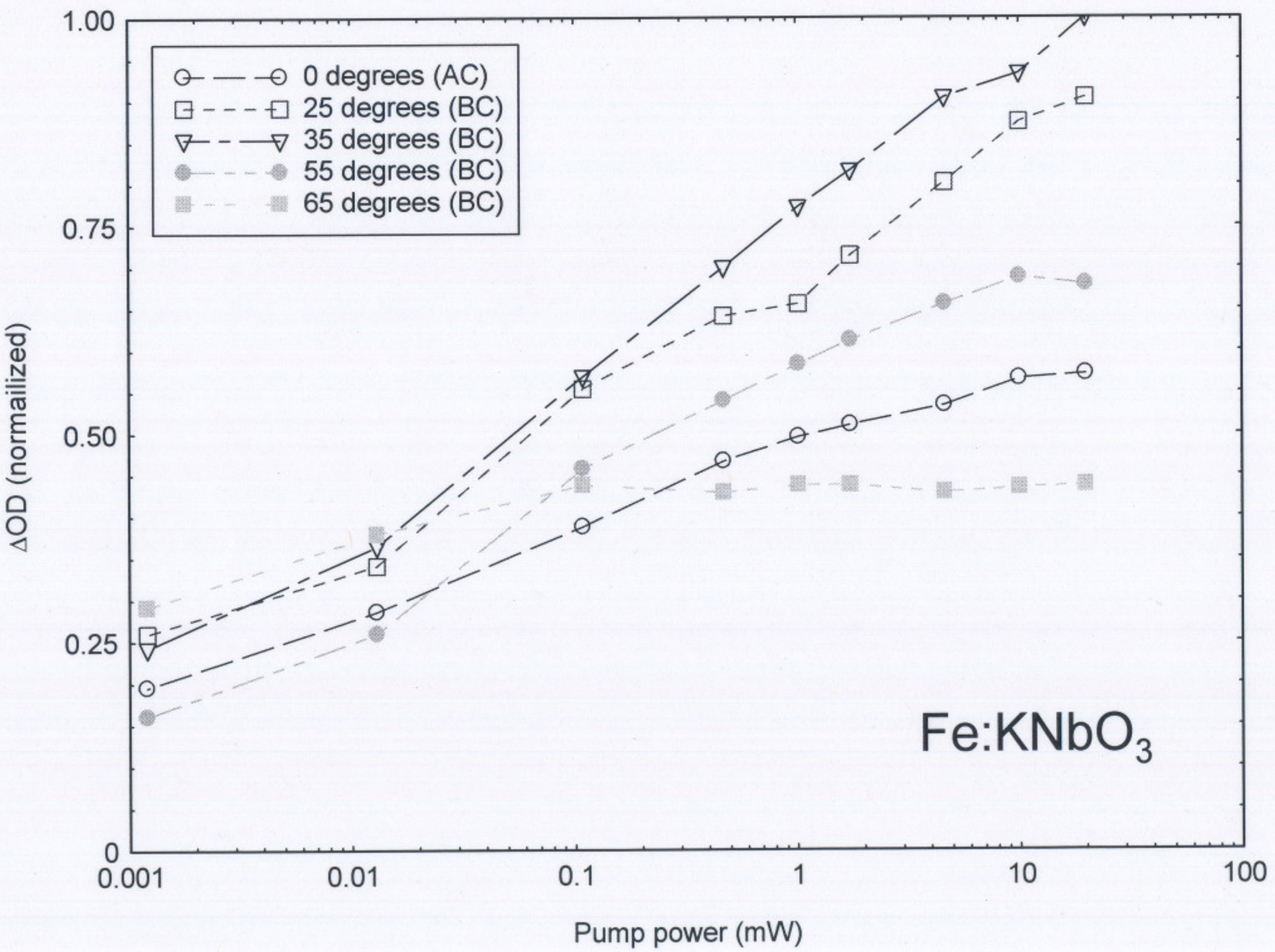
Real Off-Axis Testing



Real Off-Axis Testing - Results

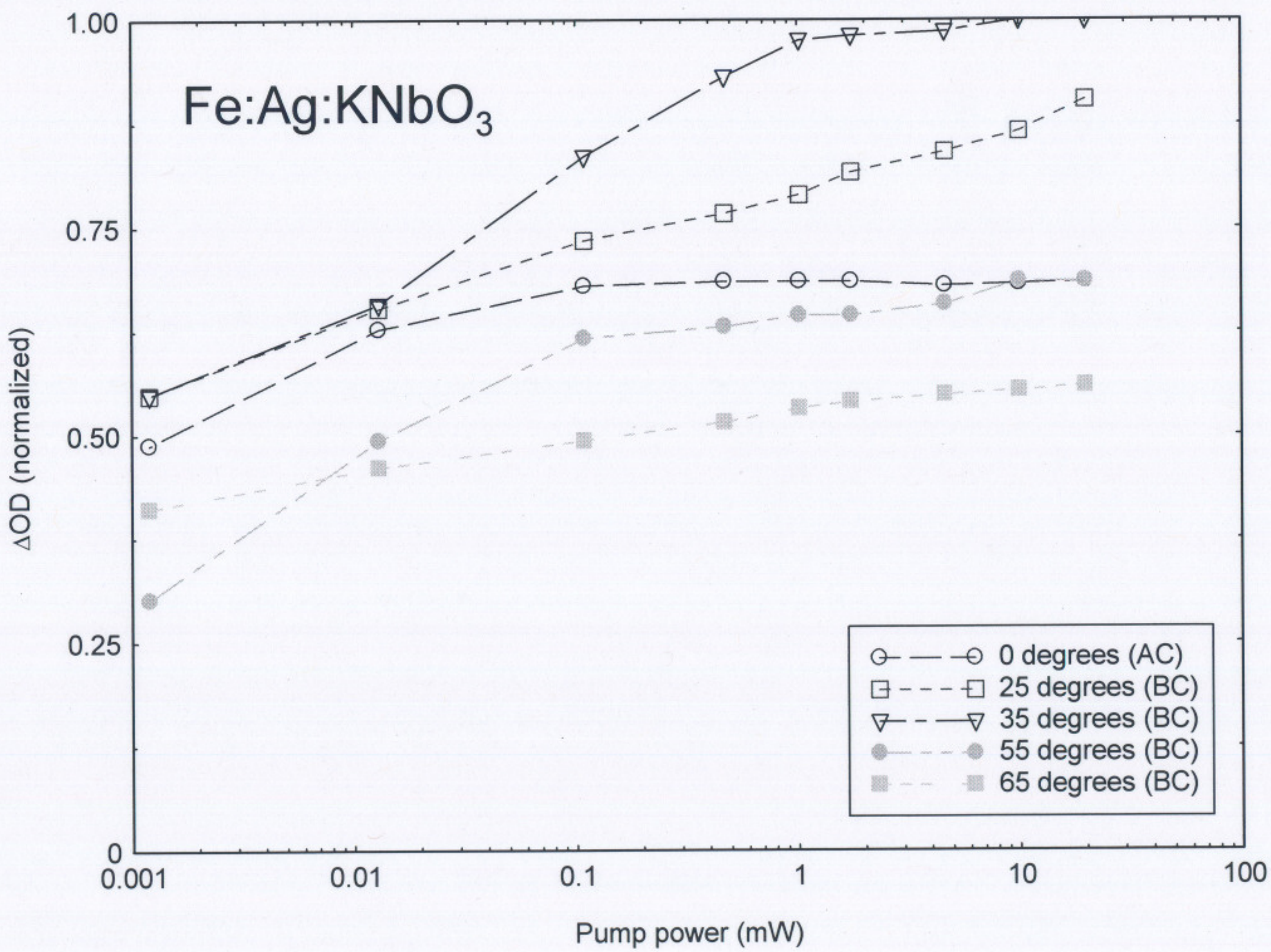


Real Off-Axis Testing - Results



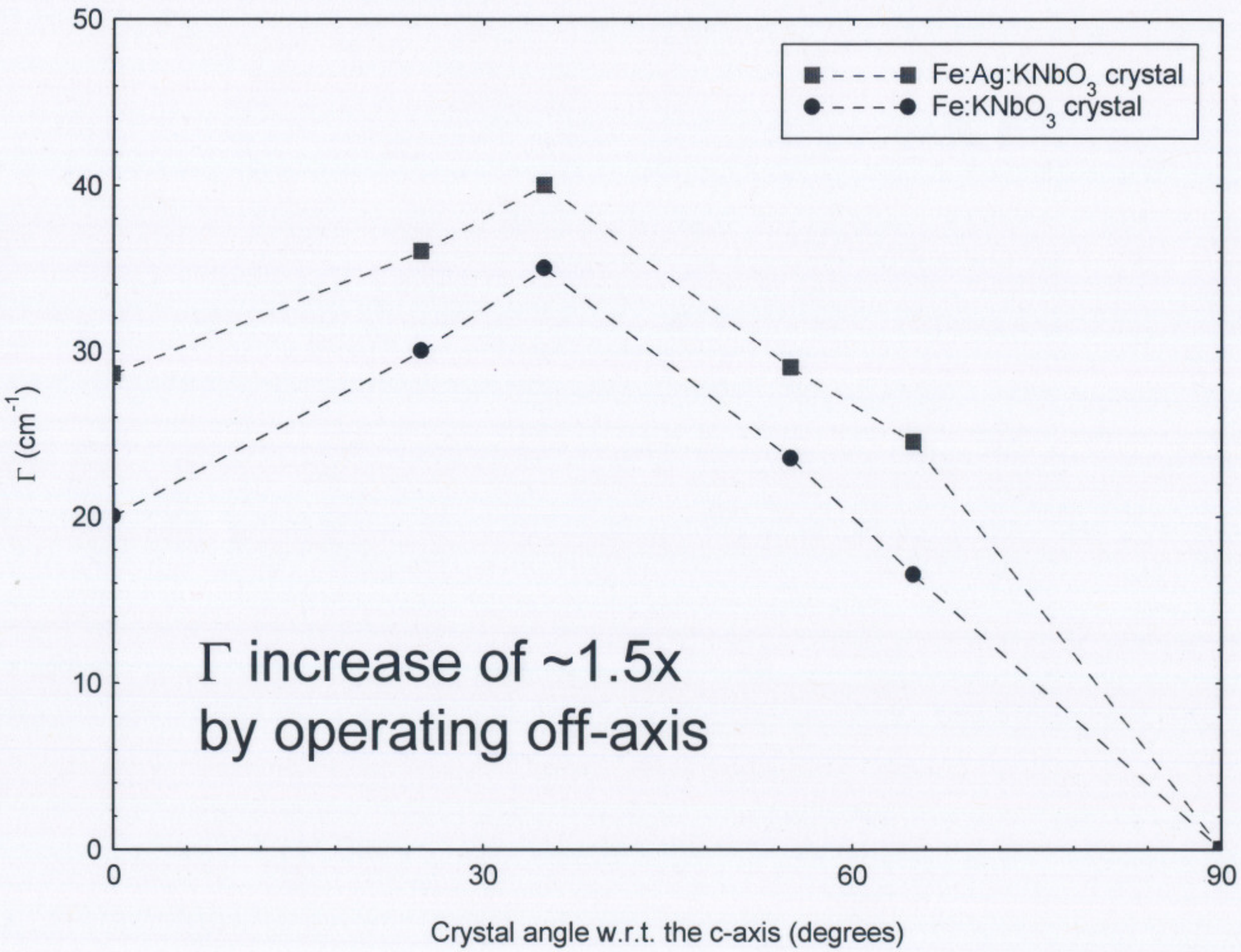
- 80% increase in ΔOD

Real Off-Axis Testing - Results



- 55% increase in ΔOD

Real Off-Axis Testing - Results



Summary

- High gain confirmed in off-axis geometries for $Fe:KNbO_3$
- Mismatch between theory and experiment for mid-range crystal angles, especially for the a-c plane*
- Large apparent variation in the effective trap density with crystal angle*
- Modified theory gives a good fit to experimental data*
- Mechanism for trap density anisotropy is uncertain, but may be due to stochastic layering of impurities during crystal growth*, or from the Franz-Keldysh Effect

* G. Cook, J. L. Carns, M. A Saleh, D. R. Evans, accepted for Phys. Rev. B, 2006